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AGRICULTURAL MEMORANDUM NO 929

The climatology of field haydrying I: The derivation of a revised bulk model of haydrying

by N Thompson

1. Introduction Recent studies at Bracknell (Thompson 1979a,b,c, 1980a,b, 1981a) have resulted in the development of bulk and multi-layer models of swath drying and have demonstrated some of the problems which are outstanding in the simulation of haydrying. Despite deficiencies in knowleage or technique which have been revealed by these studies it is now necessary to proceed to the development of a concomitant method of determining the climatology of haydrying, in order to provide a useful application of the earlier work.

There are several methods of relating the success of haymaking to weather during the haymaking season. An example of simple schemes is provided by Forsdyke (1973a,b) who defined periods of 4 or 5 days with negligible rainfall as those suitable for haymaking, and produced analyses for Wales and south-west England for a ten-year period showing the average number of haydrying runs in ten-day periods during the season. Other investigators have recognised that a dry day is not necessarily a good day for haymaking. Thus, Spatz et al (1970) used accumulated vapour pressure deficit and a low rainfall criterion ($<$ 1mm per day) in order to classify haydrying periods, and presented their results as the number of cutting days in ten-day periods which would lead to field-dry hay ($\leq$ 25% moisture content, dry weight basis: dry weight basis is used for expressing moisture content throughout this Memorandum). Wilkins and Roy (1969) used a scheme similar to that of Spatz et al, but with accumulated potential evapotranspiration as the primary indicator. A somewhat more complicated method developed by Dyer and Brown (1977), relating rate of change of moisture content of a swath to PE, dewfall and rain, has been used by Dyer and Selirio (1977) to determine the number of days in given periods when hay could be cut and subsequently dried in the field successfully.

These and other methods which have been produced up to now for estimating the drying period for hay have been largely empirical, and all have shortcomings when applied practically. The basis of a more fundamental method of estimation has been described by Thompson (1981a) who constructed a multi-layer swath model to look in detail at the haydrying process and the effects of equilibrium humidity, rainfall or dewfall, transpiring stubble, and evaporation from the soil on the drying rate. He also derived from this a much simpler bulk model which lends itself to the investigation of the climatology of haydrying, provided certain modifications can be incorporated. These are chiefly the effects of transpiring stubble and soil evaporation (which the bulk model ignores at present) and a more realistic treatment of the uptake and subsequent evaporation of surface moisture absorbed by the swath time. The present Memorandum describes a modified bulk swath drying model which attempts to account satisfactorily for the processes just described: a subsequent Memorandum will describe the application of the model to the determination of the climatology of haydrying.

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2. A bulk swath-drying model for climatological applications The rate of water loss from the swath may be approximated by (Thompson 1981a).

$$E = \frac{\Delta(R_N - G) + \rho c_p \delta q' / r_a}{\Delta\lambda + 100 c_p (1 + r_s/r_a)/Q} \qquad (1)$$

: the notation is conventional, but with the following exceptions

$$\delta q' = q_{sat}(T = T(z)) - 100\, q(z)/Q \qquad (2)$$

Q = equilibrium relative humidity (per cent)

z = reference height for meteorological data used to evaluate (1), usually assumed to be screen height

Equation (1) may be modified along the lines indicated by Thompson (1981b) to allow for errors in the estimation of net radiation resulting from the usual approximation that surface and screen temperatures are equal when calculating long-wave radiation from the surface. The revised equation is

$$E = \frac{\Delta(R_N - G) + \rho c_p \delta q' (1 + B r_a/\rho c_p)/r_a}{\Delta\lambda + 100 c_p (1 + r_s/r_a)(1 + B r_a/\rho c_p)/Q} \qquad (3)$$

Equation (3), used in conjunction with the form of r_a for neutral stability

$$r_a = \frac{6.25}{U(10)} \ln\left(\frac{10}{z_o}\right) \ln\left(\frac{z}{0.2 z_o}\right) \qquad (4)$$

with z_o the roughness length for momentum transfer (~ 0.1 x height of vegetation), gives estimates for E with acceptable accuracy for the present purpose (usually within a few percent of values derived using values of r_a corrected for stability).

3. Treatment of wetted swaths Equations (3) and (4) give the rate of water loss from a swath lying on dry soil without a transpiring stubble, and in these circumstances, and provided r_s is correctly specified, may be used to estimate the duration of the drying period to 25% moisture content. However there are fundamental difficulties in applying the main equation when swath and soil are wetted by rain, or when transpiration from stubble occurs. r_s is zero when the swath is thoroughly wetted, and Q is put equal to 100% in recognition of the fact that the calculated moisture loss is from the swath suface rather than the swath tissue. The calculation refers strictly to the loss of surface moisture from the swath only when simultaneous evaporation from the underlying soil is negligible. This is a good approximation for a fairly dense swath, but is less accurate for a sparser swath intercepting less radiation. A first-order correction to E for sparser swaths is obtained by assuming that the water loss is related directly to the amounted of radiation intercepted by the swath, and

that for leaf area indices $\xi \geq 5$ equation (1) can be applied directly. Then, writing E' for the rate of water loss from a sparser swath,

$$E'/E \simeq (1-\exp(-0.6\xi))/(1-\exp(-0.6\times 5))$$

$$= 1.05\,(1-\exp(-0.6\xi)) \qquad (5)$$

(e.g. Thompson 1981a).

An additional calculation is required to estimate the simultaneous uptake of the surface moisture by the swath tissue. In the simulations described by Thompson (1981a) the simplifying assumption was made that this uptake was at the same rate as vapour absorption in a saturated atmosphere, but there was some indirect evidence from a comparison of the simulated outputs with limited experimental data on swath drying that the estimated rate of uptake of this surface moisture was then underestimated. There appear to be few experimental data on this point, but van Elderen et al (1972) gave some results from laboratory experiments which may be used here. They suggested that a thoroughly wet swath would absorb moisture at a rate, E_w per kg of swath dry matter per hour, linearly dependant on the difference between the maximum possible tissue moisture content W_{max} and the actual moisture content W (%), so that

$$E_w = 0.01a\,(W_{max}-W) \qquad (6)$$

A suggested value for W_{max} was 900%, but this may be too high for recently-cut grass at a very early stage of wilting: it may be more realistic to use for the latter say 600% (around the highest moisture content expected for unwilted grass): a value of 0.04 kg/kg dry matter was given for a. According to equation (6), a very dry swath when thoroughly wetted would absorb moisture at a rate of 0.35 kg per kg of dry matter per hour.

A good cut of grass contains about 5 tonnes ha^{-1} of dry matter, with a leaf area index of about 5. The maximum amount of surface water it can hold after drainage is 0.1-0.2 mm equivalent per unit leaf area index, or roughly 1-2 kg/kg dry matter: a value of 1.5 kg/kg which was found by van Elderen et al will be used here. If the rainfall is prolonged and the swath is initially fairly dry then a substantial amount of surface moisture will be absorbed into the swath material. Now according to Equation (6) a dry swath thoroughly wetted by rain in a short period will, in the absence of subsequent evaporation of surface moisture, absorb all this moisture in 4 or 5 hours. Thus the duration of rainfall, as well as the amount, is required to assess the subsequent increase in swath tissue moisture. Lighter falls of rain will not completely soak the swath, leading presumably to a rate of uptake of water by the tissue less than that given by Equation (6). However, in order to keep the model simple it will be assumed that any fall of rain will wet all surfaces of the swath, albeit with a very thin film if the amount of rain is small. The rain will be apportioned equally to each hour, for convenience, and assumed to fall almost instantaneously at the start of the hour. Then the hourly uptake of water by the swath material is the smaller of E_w and the interception (Thompson 1981a)

$$I \simeq I_c\,(1-\exp(-R_h/I_c)) \qquad (7)$$

where I_c is the interception capacity ($\simeq$ 1.5 kg/kg dry matter) and R_h is the hourly rainfall (expressed in kgm^{-2}). When I exceeds E_w the free water on the swath at the end of the hour is

$$I' = I - E_w \qquad (8)$$

which, according to eq (7), is the interception produced by a rainfall

$$R' = I_c \ln \left(I_c/(I_c - I') \right) \qquad (9)$$

The interception is calculated at the start of the next hour by adding R' to R_h and using the value in Equation (7): it is assumed that no evaporation occurs while rain is falling. Calculation then continues as before, being repeated for each hour until rainfall ceases. From this point it is assumed that water continues to be absorbed by the swath according to Equation (6) but is evaporated from the surface at a rate E_o obtained from Equation (3) with $r_s = 0$.

Some laboratory experiments carried out by Brück and van Elderen (1969) showed that surface water absorbed by a swath's tissue was evaporated less rapidly than free surface water, but considerably more rapidly than water bound in a dry swath's tissue. The rate of water loss declined as the tissue moisture content decreased towards the original value before the swath was wetted, but it was not possible to estimate from the data given the corresponding resistance to loss from the swath of this loosely-bound moisture. However it is plausible to assume that at maximum uptake (tissue moisture content $\sim$ 900%) the resistance to initial water loss is close to zero, and increases as the moisture content declines. A relation of the form

$$r_s = \frac{b}{W} \left(W_{max} - W \right) \qquad (10)$$

might be postulated: it mimics the pattern of expected resistance to loss of the tightly-bound tissue moisture at low moisture contents, which is plausible, and gives zero resistance at $W = W_{max}$ but the value for b remains to be estimated.

4. Treatment of soil moisture evaporation and stubble transpiration. The method suggested by Grant (1975) for transpiring barley may be adapted for application to a swath lying on damp soil and transpiring stubble. Grant found an approximate relation

$$\frac{1}{r_s} = \frac{c}{r_{ss}} + \frac{d}{r_{sc}} \qquad (11)$$

where

r_s = bulk surface resistance

r_{ss} = resistance of bare soil

r_{sc} = resistance of a crop dense enough to intercept all radiation incident on it.

The weighting factors c and d were assumed to be equal to the fractions of incident radiation respectively transmitted and intercepted by the crop, so that $1-c = d$, with (for barley)

$$c \simeq (f)^{\ell} \qquad (12)$$

where

ℓ = leaf area index

f = a constant, with a value of about 0.7 for barley

One may attempt to adapt equation (11) for application to the case where transpiring stubble underlies the swath. A possible representation is

$$\frac{1}{r_s} = \frac{c'}{r_{ss}} + \frac{g'}{r_{stubble}} + \frac{d'}{r_{swath}^{(min)}} \qquad (13)$$

where

$r_{swath}^{(min)}$ = swath resistance when the hay is dense enough to intercept the incident radiation

d' = fraction of incident radiation intercepted by swath

$\simeq (1 - f^{\ell_{swath}})$

c' = fraction of radiation incident on soil

$\simeq (1 - f^{(\ell_{swath} + \ell_{stubble})}$

g' = fraction of radiation intercepted by stubble

$\simeq f^{\ell_{swath}}(1 - f^{\ell_{stubble}})$

$r_{stubble}$ = $r_\ell / 2\ell_{stubble}$

r_ℓ = leaf stomatal resistance of stubble

Equation (13) is a direct extension of equation (11), obtained with the assumption that stubble resistance, weighted inversely by the radiation intercepted by the stubble, may be placed in parallel with the weighted resistances for soil and swath. Some idea of how far Equation (13) falls short of an exact relation may be gained by considering the resistance pathways for water vapour flow from the swath-covered surface up to the screen height (Figure 1). The resistance equations for the "exact" representation (Figure 1a) are

$$E_{swath} = \rho \left(q_{sat}(swath) \cdot \frac{\Omega}{100} - q(0)(swath) \right) / r_{swath} \qquad (14)$$

$$E_{stubble} = \rho \left(q_{sat}(stubble) - q(0)(stubble) \right) / r_{stubble} \qquad (15)$$

$$E_{soil} = \rho \left(q_{sat}(soil) - q(0)(soil) \right) / r_{soil} \qquad (16)$$

where q_{sat} and $q(0)$ refer respectively to saturation specific humidity at the bulk temperature of the layer surface under consideration, and to the corresponding bulk specific humidity appropriate to air in contact with the material in the layer/surface. The sum of the left hand sides of these equations is E, but it is clear that little further simplification can be made because of the variations of temperature and specific humidity in the vertical between ground and top of swath, and the different resistance pathways from the surfaces of soil, stubble and swath up to the reference height. In any case each of these equations has to be used in its own version of the conbination equation, modified to account for the different bulk origins of the water vapour fluxes, and also with a set of energy balance equations, so that the model becomes essentially a 3-layer one rather than a bulk representation.

Figure 1b shows that an exact bulk description exists for a swath overlying a dry soil without transpiring stubble. The resistance representation of Eq (13) appears in Figure 1c. If the inverse weighting of resistances according to radiation intercepted is a valid assumption then a more rigorous representation based on this assumption is shown in Figure 1d. A quantitative comparison of the two treatments of resistance may be pursued as follows. It is assumed that the various resistance components are inversely weighted by the amount of radiation intercepted by the three constituents (swath, stubble, soil). Now,

$$R = \int_{h}^{z} (1/K(z-d))\, dz + \int_{z_2}^{h} (1/K(z))\, dz \qquad (17)$$

$$= R_1 + R_{SWATH}$$

where d is the zero plane displacement height ($\simeq 0.63h$) and K is the eddy diffusion coefficient. Above the swath, an expression, strictly valid for near-neutral stability, is used:

$$K(z) = k u_* z \qquad (18)$$

where $k \simeq 0.4$, leading to

$$R_1 = \frac{1}{k u_*} \ln\left(\frac{z-d}{h-d}\right) \qquad (19)$$

where

$$u_* = k\, U(10) / \ln\left(\frac{10-d}{z_0}\right) \qquad (20)$$

At the top of the swath, from Eq (18)

$$K(h) = k u_* (0.37h)$$
$$= 0.15 u_* h \qquad (21)$$

Within the canopy, assume that swath and stubble do not overlap significantly, and have their foliage unformly distributed in the vertical, with equal leaf area densities (Figure 2). Also, assume that the bulk origins of water vapour in swath and stubble are at a height above the base of each equal to 0.63 x thickness of each, by rough analogy with the zero plane displacement height. Then z_2 is given by

$$z_2 = z_1 + 0.63(h - z_1)$$
$$= 0.63h + 0.37 z_1 \qquad (22)$$

The variation of $K(z)$ with height in the canopy is assumed to be (e.g. Denmead 1976):

$$K(z) = K(h) \exp(-2.5(1 - z/h)) \qquad (23)$$

Thus,

$$R_{SWATH} = \frac{h}{2.5 K(h)} \left(\exp(2.5(1 - z_2/h)) - 1 \right) \qquad (24)$$

Similarly,

$$R_{STUBBLE} = \frac{h}{2.5 K(h)} \left(\exp(2.5(1 - 0.63 z_1/h)) - \exp(2.5(1 - z_2/h)) \right) \qquad (25)$$

$$R_{SOIL} = \frac{h}{2.5 K(h)} \left(\exp(2.5) - \exp(2.5(1 - z_2/h)) \right) \qquad (26)$$

The form of the wind profile used within the swath is that suggested by Denmead (1976):

$$U(z) = U(h) \exp(-2.5(1 - z/h)) \qquad z \leq h \qquad (27)$$

where

$$U(h) = U(10) \ln\left(\frac{h-d}{z_0}\right) / \ln\left(\frac{10-d}{z_0}\right)$$
$$= U(10) \ln\left(\frac{0.37h}{0.1h}\right) / \ln\left(\frac{100-10d}{h}\right)$$
$$= 1.3\, U(10) / \ln\left(\frac{100-10d}{h}\right) \qquad (28)$$

The boundary-layer resistances for swath and stubble are approximately (Thompson 1979a).

$$r_{b\,swath(min)} = 0.9 f_1 (Re_{swath})^{1/2} / (2\, U(z_2)\, f_{swath}) \quad (29)$$

$$r_{b\,stubble} = 0.9\, (Re_{stubble})^{1/2} / (2\, U(0.63 z_1)\, f_{stubble}) \quad (30)$$

: f_1 is the ratio of f_{swath} to f for a very dense swath, with the latter taken as ~ 7. The corresponding value for the boundary layer at the soil surface is

$$r_{b\,soil} = 0.9\, (Re_{soil})^{1/2} / U(0) \quad (31)$$

On the assumption of an average width of leaf and stem of around 0.003m, and typical soil clods of 0.02m, these equations become

$$r_{b\,swath(min)} = 6 / ((U(z_2))^{1/2} . 7) \quad (32)$$

$$r_{b\,stubble} = 6 / ((U(0.63 z_1))^{1/2} . f_{stubble}) \quad (33)$$

$$r_{b\,soil} = 33 / (U(0))^{1/2} \quad (34)$$

The comparison which has to be made is between the value for r_s (r_{s1}) given by equation (13) and that appropriate to Figure 1d:

$$r_{s2} = \left(c' / (R_{soil} + r_{b\,soil} + r_{ss}) + g' / (R_{stubble} + r_{b\,stubble} + r_{stubble}) + d' / (r_{b\,swath(min)} + r_{swath(min)}) \right)^{-1} + R - r_a \quad (35)$$

The grass-wilting experiments described by Sparks (1980) suggest that for a dense lacerated swath a value of around $10^5/W$ is appropriate for $r_{swath(min)}$: corresponding value for a swath produced by a gentle cutting system (cutter-bar mower) is about $2 \times 10^5/W$. The variation of the leaf (stomatal) resistance with incident radiation is assumed to be of the form found for cereals (e.g. Day et al 1981)

$$r_l = r_o (1 + \alpha / I) \quad (36)$$

where

I = short-wave radiation incident on stubble

$r_o \sim 150\ sm^{-1}$

$\alpha \sim 100\ Wm^{-2}$

A typical set of input values with which to evaluate r_{s1} and r_{s2} is:

$I = 200\ Wm^{-2}$

$U(10) = 3\ ms^{-1}$

$T = 20$ deg C

$r_{ss} = 100\ sm^{-1}$

$f_{swath} = 5$

$f_{stubble} = 1$

$W = 100\%$

$h = 0.2$ m

$z_1 = 0.05$ m

Then,

$r_e = 450\ sm^{-1}$

$r_{stubble} = 225\ sm^{-1}$

$r_{swath}(min) = 2000\ sm^{-1}$

$c' = 0.12,\ g' = 0.05,\ d' = 0.83$

A value for r_{s1} of 544 sm^{-1} follows from eq (13). The three components of the right hand side of eq (13) are also assumed to be roughly proportional to the contributions of soil, stubble and swath to the total evaporation from the surface (ignoring variations of temperature in the swath: a more exact partitioning is described later), leading to relative contributions to E of 0.66, 0.12 and 0.22 respectively.

z_o is approximately 0.02 m, and this leads to a value for r_a of 74 sm^{-1}. Total evaporation from the surface may then be calculated approximately from Eq (1), with $Q \simeq 100\%$ for the selected W value of 100%:

$$\lambda E_1 = \left(\Delta(R_N - G) + \rho c_p \delta q' / r_a\right) / \left(0.0009 + 0.00041\,(1 + 544/74)\right)$$

or, putting the numerator equal to A,

$$E_1 = 233A/\lambda$$

Thus, the swath evaporation is $51A/\lambda$. A similar calculation for a case with a dry soil surface ($r_{ss}=\infty$) and no stubble (g' = 0) gives a swath evaporation of $69A/\lambda$, demonstrating the reduction in swath drying when a wet soil and transpiring stubble increase the humidity near the surface.

Evaluation of the various terms in the more exact representation (eq 35) gives

$$R = 48.5, \quad R_{soil} = 140.4, \quad R_{STUBBLE} = 85.7 \quad sm^{-1}$$

$$r_{b\,soil} = 145, \quad r_{b\,stubble} = 25.6, \quad r_{b\,swath(min)} = 1.5 \quad sm^{-1}$$

Then, from eq (35), $r_{s2} \simeq 1120\ sm^{-1}$, and the relative contributions to from soil, stubble and swath are roughly in the ratio 0.36, 0.17, 0.47. The calculated value for E_2 is $134A/\lambda$ and the swath evaporation is $63A/\lambda$ or around 25% larger than the value from Eq (13). A small part of the disparity can be removed by assuming that Grant's (1975) representation of r_{ss} included a contribution due to the boundary layer of the soil surface, so that even when the soil was saturated a minimum value for the resistance was around 100 sm^{-1}. A proper value for r_{ss} for a thoroughly moist soil in eq (35) is probably near zero and on this assumption the revised value for r_{s2} becomes 990 sm^{-1} with the relative contributions from soil, stubble and swath evaporation in the proportions 0.43, 0.15, 0.42. E_2 is now $148A/\lambda$, with the contribution from swath moisture equal to $62A/\lambda$, still about 20% larger than the value given by eq (13). The corresponding value for the case with a dry soil and no stubble is $69A/\lambda$, little different from that given by Eq (13).

It is clear the estimates by the two schemes of rate of water loss from the swath may be brought closer to coincidence by adjusting the effective values of $r_{swath\,(min)}$, and on this basis eq (13) might be used: the substantial difference in the two estimates of the rate of water loss from the soil are usually of little significance in the present context. Alternatively, and better, an empirical adjustment can be made to eq (13) to take rough account of the additional resistance in the canopy indicated in Figure 1d. The suggested revised equation is

$$\frac{1}{r_{s1}} = \frac{c'}{r_{ss}'+a_1} + \frac{g'}{r_{stubble}+a_2} + \frac{d'}{r_{swath(min)}} \qquad (37)$$

a_1 and a_2 are functions of wind speed and a_2 is dependant on stubble leaf area also, but for simplicity constant values of 200 and 100 sm^{-1} will be assumed for these, with r_{ss}' = 0 for wet soil, following the discussion above. Then

$$\frac{1}{r_{s1}} = \frac{c'}{r_{ss}'+200} + \frac{g'}{r_{stubble}+100} + \frac{d'}{r_{swath(min)}} \qquad (38)$$

r_{ss}' will be a function of the soil moisture deficit in the top few centimetres or so of the soil. Following Saxton et al (1974), the rate of evaporation is assumed to be independant of soil moisture while the first 40% of the latter is lost, and then declines with further moisture removed in a manner roughly consistent with

$$r_{ss}' = 400\left(\frac{0.6\,S_{max}}{S} - 1\right)^{1.5} \qquad 0.6S_{max} > S > 0 \qquad (39)$$

where

S_{max} = maximum soil moisture available for bare soil evaporation (assumed to be 25 mm)

S = soil moisture remaining

The soil moisture status just prior to cutting is also needed in order to determine r_{ss}' . As a rough approximation it will be assumed that the maximum water which can be extracted by plants alone from this surface layer is 60% of the total moisture, or 15 mm. It is usual to assume that grass will extract up to 125 mm from the whole soil profile, for medium soils, with the first 50 mm at full potential rate, and the remainder at a reducing rate (Thompson et al 1981). It is convenient to assume a similar process for extraction of water in the near-surface layer by plants in order to determine the moisture content of this layer at cutting time. When this surface layer is completely dry, then up to the first 10 mm of rain will be assumed evaporated at a rate given by $r_{ss}' = 0$: evaporation of rain beyond this is given by eq (39).

Up to this point the assumption has been made that the swath tissue water content is large enough for absorption of water vapour from a near-saturated atmosphere not to occur ($Q \simeq 100\%$). As the swath dries this is no longer the case, and water uptake will take place when ambient humidity rises above equilibrium humidity (eq (1),(2)). Thompson (1981a) showed that for a swath overlying dry soil without transpiring stubble

$$E \propto \frac{1}{r_s} \cdot \frac{Q}{100} \qquad (40)$$

and this suggests that a version of eq (38) to be used for all values of swath water content is

$$\frac{1}{r_{s1}} = \frac{c'}{r_{ss}'+200} + \frac{g'}{r_{stubble}+100} + \frac{d'Q}{100\, r_{swath(min)}} \qquad (41)$$

Modification of the numerator of the combination equation is necessary in order to model simultaneous loss of moisture from soil and stubble and uptake by swath, which can occur at high ambient humidities. The basic equation (eq (1)) may be rewritten

$$E = \frac{\Delta(R_N-G) + \rho c_p ((a)+(b))\delta q + (c)\delta q')/r_a}{\Delta\lambda + 100 c_p (1 + r_s/r_a)/Q} \qquad (42)$$

when (a) and (b) are weighting factors for loss of water from soil and stubble. and (c) is the corresponding factor for moisture loss from the swath. The weighting factors are assumed to be implicit in eq (38), and rewriting the equation as

$$\frac{1}{r_{s1}} = \underset{\text{SOIL}}{x_1} + \underset{\text{STUBBLE}}{x_2} + \underset{\text{SWATH}}{x_3} \qquad (43)$$

are:

$$\left.\begin{aligned} \textcircled{a} &= x_1 r_{s1} \\ \textcircled{b} &= x_2 r_{s1} \\ \textcircled{c} &= x_3 r_{s1} \end{aligned}\right\} \quad (44)$$

Eq (42) (or the equivalent version which includes the effects of surface heating, cf eq (3)) provides a bulk formulation for estimating the net loss of moisture from the soil/stubble/swath system. Its use requires separation of the contributions to E from the three system components. This cannot be done exactly in any simple way but in view of the approximations up to this point the requirement is for a method which gives correct answers (a) when swath evaporation dominates (dry soil, no stubble) and (b) when the foliage is wet, and also offers a plausible interpolation in cases where all three components of the system make significant contributions to E. The case with wet foliage is straightforward: soil evaporation is then ignored and the following relations are used:-

$$\left.\begin{aligned} r_s &= 0 && \text{(swath and stubble wet)} \\ \frac{1}{r_s} &= \frac{g'}{100} + \frac{d'}{r_{swath(min)}} && \text{(swath dry, stubble still wet)} \end{aligned}\right\} \quad (45)$$

Moisture will have been absorbed by the swath after wetting and will be relatively loosely bound, so that $r_{swath(min)}$ in the second part of eq (45) is smaller than for a swath not recently wetted; there will be little error in assuming that E is then partitioned between evaporation of water intercepted by the stubble, and loss of moisture loosely bound in the swath in the ratio $g'/100 : d'/r_{swath(min)}$. This ignores the equilibrium humidity of the swath, but this is realistic because the equilibrium humidity is unlikely to be important while the loosely-bound swath moisture evaporates, usually slower than the stubble loses its intercepted moisture. The most common case will be when there is no intercepted moisture and then a plausible simple partitioning follows from an inspection of eq (38) and (42) which suggests that soil, stubble and swath evaporation are roughly in the ratio $c'\delta q/(r_{ss}+200) : g'\delta q/(r_{stubble}+100) : d'\delta q'/r_{swath(min)}$

5. <u>Discussion and concluding remarks</u> The revised bulk formula which follows from eq (3) and (42) is

$$E = \frac{\Delta(R_N-G) + \rho c_p((\textcircled{a}+\textcircled{b})\delta q + \textcircled{c}\delta q')(1+Br_a/\rho c_p)/r_a}{\Delta\lambda + 100 c_p (1+r_s/r_a)(1+Br_a/\rho c_p)/Q} \quad (46)$$

This is used with an expression for Q (Thompson 1981a).

$$Q = 100\left(1-\exp\left(-0.05W(1+0.017(T(o)-20))\right)\right)^{0.85} \quad (47)$$

where $T(o)$ is the bulk swath temperature and W is the percentage water content (dry weight basis). $T(o)$ is not known but may be derived from the expressions

$$\begin{aligned} H+\lambda E &= R_N - G \\ T(o)-T(z) &= Hr_a/\rho c_p \\ &\simeq (R_N-G)r_a/\rho c_p \end{aligned} \quad (48)$$

for a dry swath, for which λE is small compared to H. The determination of a climatology of haydrying using the revised bulk model is straightforward in principle, and will be described in a later Memorandum, but it is clear from the present report that in practice a satisfactory estimation of the climatology requires more data on aspects of uptake and loss of moisture from swaths than appear to be available at present. It is hoped that these data will emerge from experiments being carried out at the Grassland Research Institute.

Any comments or suggestions on this paper should be referred to the author.

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October 1981

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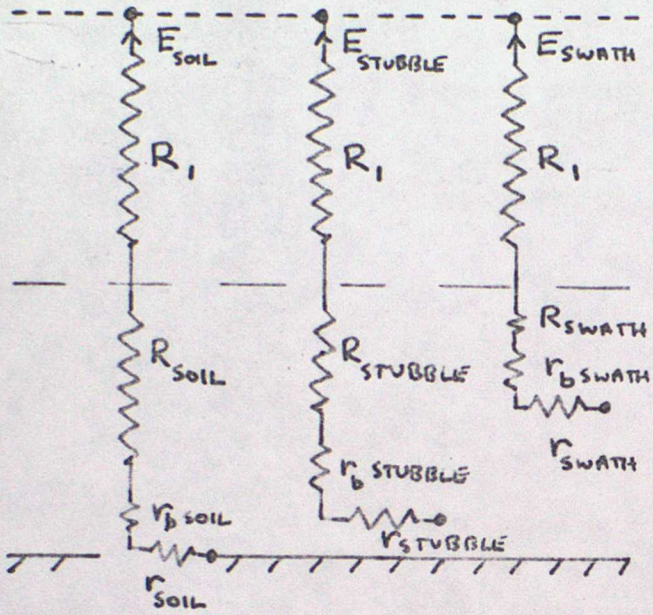
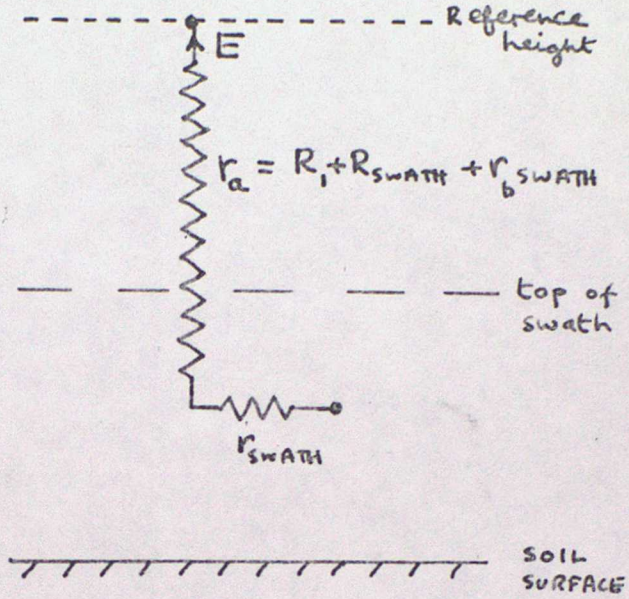
R: resistances associated with turbulent transfers within air spaces of swath and stubble, and above the swath

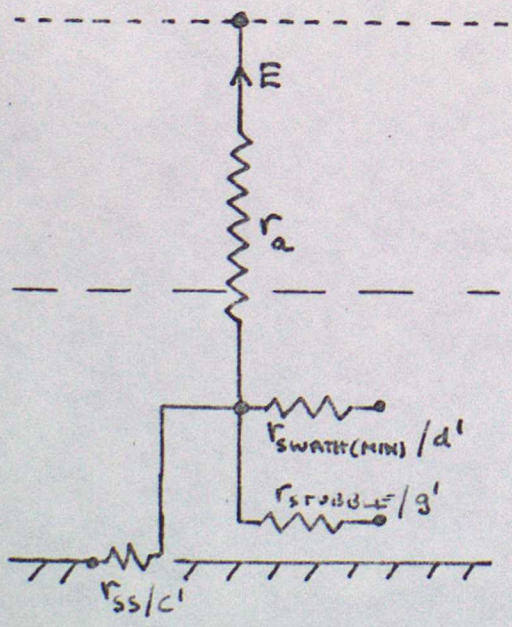
r_b: resistances associated with transfers through boundary layers surrounding leaves and stems, or at the soil surface



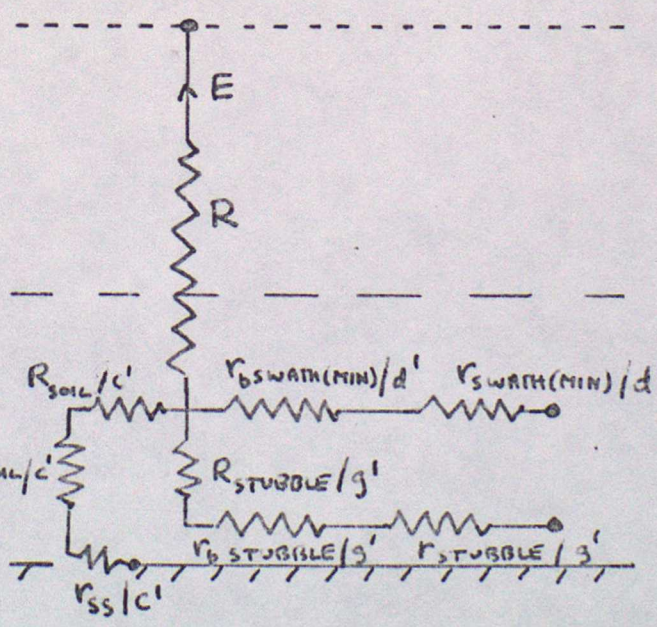
a. "Exact" resistance analogue



b. No stubble, dry soil



c. Equation (13)



d. The more exact representation, which simplifies to eq (13)

Figure 1 Resistance networks for a swath-covered surface

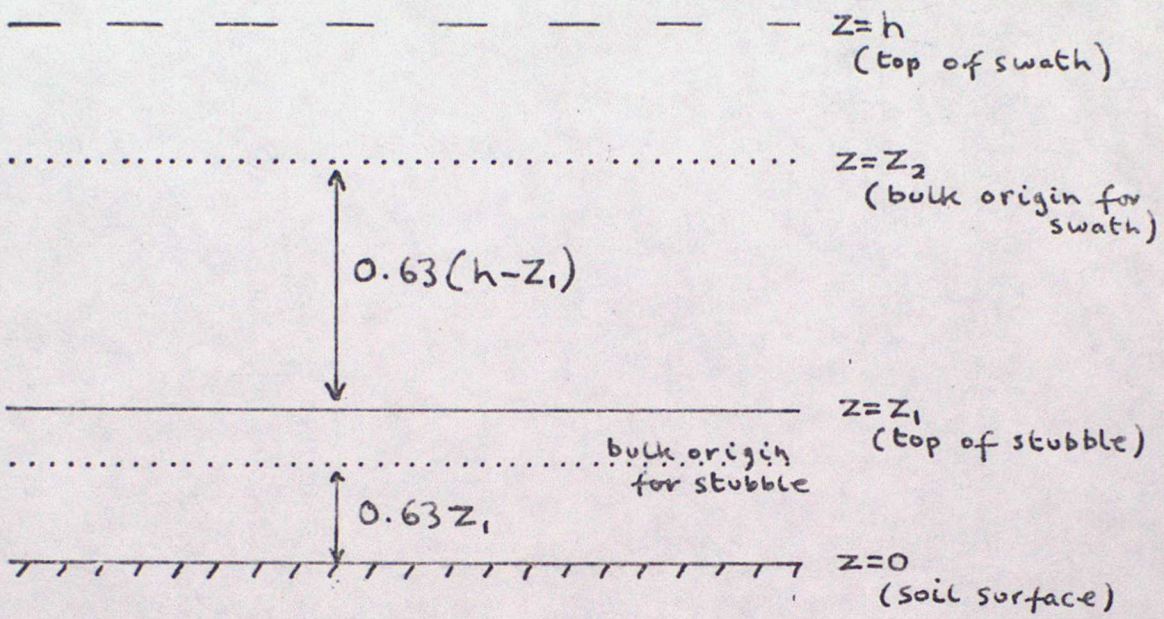


Figure 2 Swath and stubble